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SOURCE-REGION EMP COUPLING RELATED TESTS: RECTANGULAR GEOMETRY, (U)

SEP 77 J F DIETZ, G MERKEL, D J SPOHN

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes a series of source-region EMP experiments, which were conducted at the Defense Nuclear Agency's AURORA Flash X-Ray Facility. Measured data are compared with pretest calculations of the predicted responses of simple rectangular gamma-thick and gamma-thin structures that were exposed to ionizing radiation. Predicted values of Compton current also are compared with next page

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data obtained by using a Compton diode and Rogowski coils in collimated and uncollimated configurations.

FOREWORD

This report describes the tests conducted at the AURORA Flash X-Ray Facility in support of the Tactical Environment Multiple Systems Evaluation Program funded jointly by the Defense Nuclear Agency and the U.S. Army Materiel Development and Readiness Command. The tests were conducted during early December 1975 by the authors and Leedy Ambrose of the Harry Diamond Laboratories. The experimenters thank the AURORA staff for their kind assistance during the tests.

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1. OBJECTIVES

The test described in this report was performed in support of the Tactical Environment Multiple Systems Evaluation Program (TEMSEP), a program at the Harry Diamond Laboratories (HDL) directed toward the analysis and testing of the vulnerability of tactical military systems to the effects of electromagnetic pulse (EMP) when exposed to nearby nuclear detonations.

The purpose was primarily to test the effectiveness of the instrumentation to be used in a more extensive source-region EMP simulation-related AURORA test planned for March 1976. In the event that the instruments failed to perform adequately, necessary modifications could be completed before the start of the March test.

The most important instrument to be evaluated was a cathode follower amplifier to be utilized as a matching element in an attempt to make high impedance voltage measurements in the environment of the Defense Nuclear Agency's AURORA Flash X-Ray Facility at HDL. This amplifier was to be evaluated during an attempt to measure the voltage generated between a conducting body and a conducting enclosure within which it was suspended.

Another instrument to be evaluated was a newly constructed Compton diode sensor which was to be utilized to measure Compton current densities. The output of this instrument was to be correlated with results obtained with thermoluminescent dosimeters (TLD's) and Rogowski coils.

A secondary objective of these experiments concerned the investigation of the source distribution of the AURORA radiation, by using collimated TLD's and a collimated Rogowski coil. In addition, the experiments tested equivalent circuit models for source-region coupling, such as that developed by Conrad Longmire of Mission Research Corp.[1] and presently being extended at HDL by Monti Wilson. Since the test configuration being utilized to evaluate the cathode follower amplifier was amenable to equivalent circuit analysis, the short-circuit current was to be measured during some shots.

2. TEST CONFIGURATION

The primary test geometry consisted of a box 6 × 6 × 6 in. (15.2 × 15.2 × 15.2 cm) constructed of 1/4-in. (0.6-cm) aluminum, suspended on nylon rope in a 26-in. (66-cm) square conducting upper chamber of a two-chamber radio frequency interference (RFI) shielded box. The inner aluminum box, located in the center of the upper

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[1] *C. L. Longmire, Direct Interaction Effects in EMP, Mission Research Corp. LANC-N-12 (November 1973).*

chamber, was connected with a thin wire to a BNC feed-through connector to the lower chamber where the cathode followers were located. The cathode follower was connected to a cable running to the data room, where the cable was ultimately terminated (fig. 1). The two chambers were separated by a 1-in. (2.5-cm) aluminum partition. The suspended 6-in. (15.2-cm) aluminum box was employed in two modes: one with the box empty so that it was thin with respect to the absorption range of the γ radiation and another with the box filled with lead so that it was thick compared with the absorption range of the radiation. The outer RFI enclosure was of double-wall galvanized sheet metal construction with separate RFI gasketed entry ports in the two chambers and a cable port in the lower chamber. The upper chamber was exposed directly to the radiation, but the lower chamber was shielded on the exterior, with 4 in. (10.2 cm) of lead adjacent to the front and the two sides, and on the interior, with 2 in. (5.1 cm) of lead adjacent to the top, the sides, and the bottom.

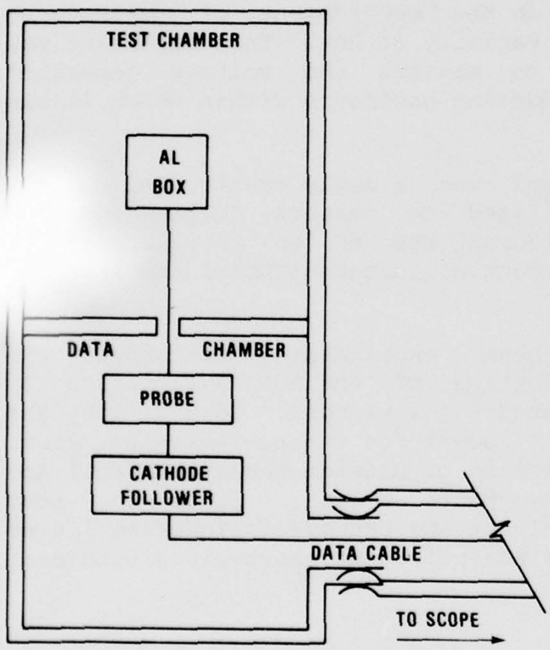

Figure 1. Primary test geometry.

The data cables extended through the data cable port down through a 4-in. (10.2-cm) thick lead chimney through the floor and along trenches covered with 2 in. (5.1 cm) of steel to the data room wall. In addition, the cables were wrapped with two layers of RFI zip tubing terminated on one end at the inner and the outer layers of the experimental chamber and on the other end at the test cell wall (fig. 2). Also, two BNC and two type "N" feed-through connectors were placed in the side of the lower chamber to be used with the externally placed Rogowski coils and the Compton diode. Two gas ports were installed in the upper chamber: one in the side near the bottom and one on the top. The experimental chamber was placed on the center axis of the AURORA test cell with the front of the chamber located at the 700-rad total dose line. The chamber was elevated so that the center of the inner aluminum box was at the axis of the γ radiation (approximately 70 in.--1.8 m--from the floor). The Compton diode and Rogowski coils were placed on a wooden cart approximately 6 ft (1.82 m) from the experimental chamber and approximately 70 in. (1.8 m) from the floor, at the 500-rad total dose

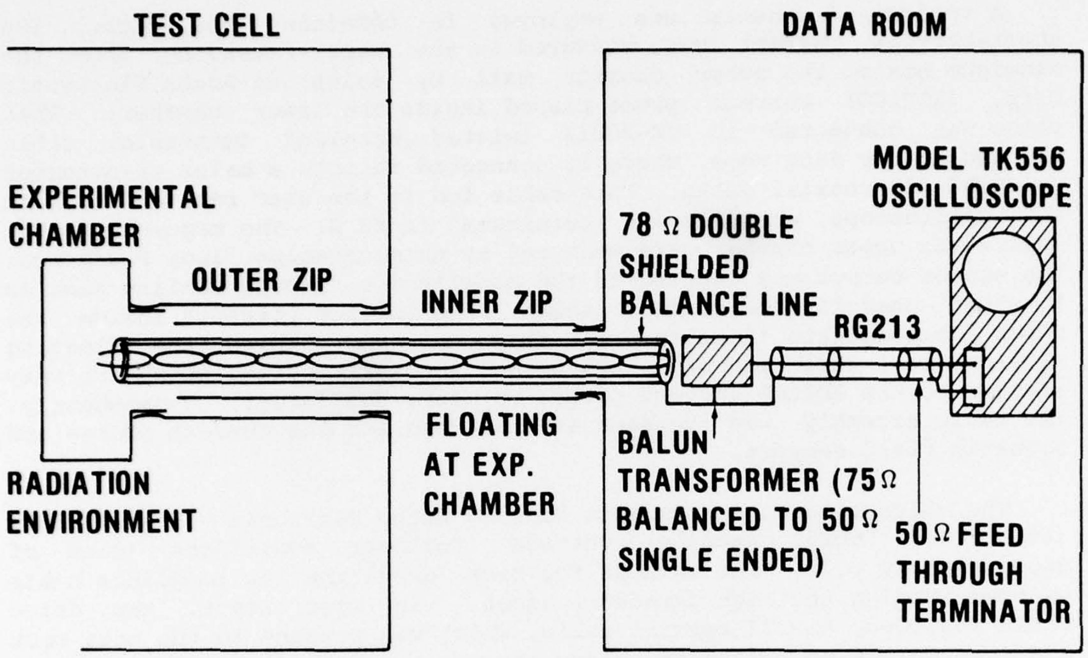

Figure 2. Cable arrangement between test cell and data-taking room. (The 78-Ω double-balanced line is used for the Rogowski coil measurements. The cathode followers and the Compton diode feed the coaxial lines.

line, but not on the axis of the radiation. These sensors were connected to the lower chamber with exposed cable (no zip tube). The collimated dosimeter experiment consisted of seven TLD's, three located at the ends of holes drilled through 2 in. (5.1 cm) of lead, three at the ends of holes drilled through 4 in. (10.2 cm) of lead, and one with no collimation. The experiment was located near the Compton diode. The axes of the collimating holes were oriented along radii to the focus of the radiation source (the hot spot). The entire experimental setup was backed with 2-in. (5.1-cm) lead bricks to shield the dosimeters from scattered radiation.

These measurements were made during the test series: short-circuit current from the inner box to the outer box, open-circuit voltage between the inner and the outer boxes, magnetic fields and Compton currents inside the upper chamber, and Compton current outside the experimental chamber. Total dose measurements were made at various locations inside and outside the experimental chamber, as well as at the peripheral Compton diode and Rogowski coil locations.

A variety of sensors was employed in obtaining the data. The short-circuit current was measured on the wire extending from the aluminum box to the outer chamber wall by using an Adams Electronic Corp. (ADELCO) current probe placed inside the lower chamber. This probe was connected to VE-20072 twisted shielded twin-axial cable running to the data room, where it connected through a balun transformer to an RG-213 coaxial cable. This cable led to the user rack and then to the oscilloscope, where it was terminated in 50 Ω. The magnetic fields inside the upper chamber were measured by using Moebius loop $\dot{B}$ sensors. The sensor output was carried to the oscillscope through cabling similar to that used for the current probes. The Compton currents inside the upper chamber (specifically, in front of and behind the floating aluminum box) were measured by using Rogowski coils, which are very similar to the ADELCO current probe, but somewhat larger. Consequently, the cable assembly was the same as that used for the current probes and magnetic field sensors.

The voltage measurements were made by using Tektronix voltage probes (P6006 and P6015) feeding cathode follower amplifiers (gain of approximately 0.7). The cathode follower drove the low impedance cable without loading the high impedance input. In most tests, the drive cable was 50-Ω, RG-223 coaxial cable, which was patched to the user rack and then to the oscilloscope, where it was terminated in 50 Ω. In one test, in an attempt to lower the noise level on the cable, the cathode follower drove a 72-Ω twin-axial cable with baluns at both ends.

The noise levels induced on representative cables also were noted. The noise was measured by recording the induced signal with the sensor disconnected or short-circuited, but with the cable remaining in its normal configuration.

The total dose was measured during each shot at strategic locations in and around the experimental chamber by using TLD's furnished by AURORA. High dose-->50 rads (Si)--or low dose--<50 rads (Si)--TLD's were used where appropriate.

3. PRETEST ANALYSIS AND CHECKOUT

3.1 Predictions

Prior to the test, a series of calculations was performed to predict the response of the various instruments and the test set to the radiation environment. These calculations served as a basis upon which to judge the experimental data, as well as an indication as to the expected signal level for setting the oscilloscope. The calculations addressed the basic concentric box test set response by using a quasi-static model and an equivalent circuit model. The Compton diode,

the collimated Rogowski coil, and the Rogowski coil sensors were treated with simple coupling models.

3.1.1 Quasi-static Model

3.1.1.1 γ-Thick Calculations

Voltage.--Because of the relatively slow rise time of the AURORA radiation pulse, it was assumed that calculations of voltages generated between the inner and the outer boxes and of the current generated on the inner box could be treated quasi-statically. Since pretest calculations were done merely to produce rough estimates of oscilloscope voltage settings, a simple static model was developed to generate voltage and current predictions.

If the region between the boxes is a perfect vacuum with no conductivity, the voltage generated between the inner and the outer boxes is equal to

$$V = Q/C \ , \tag{1}$$

where Q is the total charge deposited and C is the capacitance of the boxes. Since the total charge deposited is equal to the time integral of the intercepted current, if the inner box is γ-thick and the outer box is γ-thin, the total charge deposited on the inner box is given by

$$q = \int_0^T \left[J(t) \cdot A \right] dt \ ,$$

where T is the width of the radiation pulse, J is the Compton current density at the front of the inner box, and A is the area of the front face of the box. Since the Compton current density generated in air is equal[1] to

$$J = -2 \times 10^{-8} \ \dot{\gamma} \ , \tag{2}$$

where $\dot{\gamma}$ is the dose rate, the total charge deposited is given by

$$q = 2 \times 10^{-8} \ D_\gamma A \ , \tag{3}$$

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[1] *C. L. Longmire, Direct Interaction Effects in EMP, Mission Research Corp. LANC-N-12 (November 1973).*

where D_γ is the total radiation dose in rads (Si). The peak voltage generated between the boxes, then, is given by

$$V_p = 2 \times 10^{-8} D_\gamma A/C \ . \tag{4}$$

It was assumed that the capacitance of the two boxes was approximately equal to the capacitance of two concentric spheres, each having a surface area equal to the surface area of one of the boxes. Since the two boxes were cubes of edge length 6 and 26 in. (15.2 and 66 cm), spheres of equal surface area would have radii of 0.105 and 0.457 m, respectively.

The capacitance of a sphere within a sphere is equal[2] to

$$C = 4\pi\varepsilon_0 \frac{r_1 r_2}{r_2 - r_1} \ , \tag{5}$$

where ε_0 is the permittivity of free space and r_1 and r_2 are the radii of the spheres. Thus, the capacitance of the boxes, assuming that they are spheres with the above-mentioned radii, is equal to 15.2 pF.

The boxes were to be placed so that the dose on the front of the inner box would be 500 rads (Si). With D = 500 rads (Si), $A = 0.023\ m^2$, and $C = 1.52 \times 10^{-11}$ F, equation (4) yielded a peak voltage of 15.4 kV.

Because the region between the cylinders was to be filled with 1 atm of SF_6 or with 1 atm of dry air, it was necessary to modify this result. Since the electron attachment rate of SF_6 is very large, it was assumed that the conductivity of the region between the boxes would be small, so that the voltage calculated above would not be reduced significantly. It was estimated that the peak voltage generated would be 7 to 8 kV.

When the region between the boxes is filled with air, the voltage generated between the inner and the outer boxes is reduced because some charge flows through the ionized, conducting air between the boxes. The peak voltage generated is then

$$V_p = \frac{1}{C}\left(q - q_L\right) \ , \tag{6}$$

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[2]*W. P. Smythe, Static and Dynamic Electricity, McGraw-Hill Book Co., Inc., New York (1968), 27.*

where q is the total charge deposited on the inner box and q_L is the leakage charge.

The leakage charge is given by

$$Q_L = \int_0^T \sigma E \, dt \ , \tag{7}$$

where σ is the air conductivity in the region between the cylinders and E is the electric field in this region. If the electric field between the boxes is approximately equal to V/d, where V is the voltage generated between the boxes and d is the distance between the boxes,

$$q_L = \frac{1}{d} \int_0^T \sigma V \, dt \ .$$

The ionization rate, Q, in ion pairs per cubic meter second produced in the region between the boxes is equal to*

$$Q = 2.25 \times 10^{15} \, \dot{\gamma},$$

and the peak number density of electrons (N_{ep}) produced in this region is given by

$$N_{ep} = Q/\alpha_e \ ,$$

where α_e is the electron attachment rate in air. Since it can be assumed that most of the conductivity in the region between the boxes is due to electrons, the peak conductivity (σ_p) in mhos per meter in this region is equal to

$$\sigma_p = 1.6 \times 10^{-19} N_{ep} \mu_e \ ,$$

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*C. L. Longmire, *A Simple Analysis of the Blue Cylinder Experiments*, Mission Research Corp. AURORA EMP Memorandum 3 (October 1975).

where μ_e is the electron mobility. If the electron attachment rate is equal to $8 \times 10^7\ s^{-1}$ and the electron mobility is $0.6\ m^2/V\ s$, the peak conductivity is equal to

$$\sigma_p = 2.73 \times 10^{-12}\ \dot{\gamma}.$$

If the average conductivity can be approximated by $\sigma_p/2$, and if the average voltage can be approximated by $V_p/2$, then equation (7) becomes

$$q_L = 6.8 \times 10^{-13} D_\gamma V_p/d\ .$$

When this equation and equation (3) are substituted into equation (6), the result is the following equation for the peak voltage:

$$V_p = 2 \times 10^{-8} A - 6.8 \times 10^{-13} V_p/d\ D_\gamma/C\ .$$

Solving for V_p yields

$$V_p = \frac{2 \times 10^{-8} A d D_\gamma}{Cd + 6.8 \times 10^{-13} D_\gamma}\ . \qquad (8)$$

The peak voltage generated at the 500-rad (Si) location would then be 170 V.

In this and in all subsequent calculations, any boundary layer effects have been neglected.

Current.--When the inner box is γ-thick, the short-circuit current flowing between the inner and the outer boxes should equal the Compton current intercepted by the inner box. Thus, the current would be given by

$$I = JA\ , \qquad (9)$$

where J is calculated from equation (2). At the 500-rad (Si) location, the current should be 1.6 A.

In this and all subsequent calculations of coupled current, electromagnetic coupling effects have been neglected.

3.1.1.2 <u>γ-Thin Calculations</u>

<u>Voltage</u>.--Since the side plates of the aluminum inner box are 6 in. (15.2 cm) long and the density of aluminum is 2.7 g/cm^3, the projected mass per unit area of these plates is 41 g/cm^2. Since this value is neither small nor large compared with 30 g/cm^2, which is a typical energy absorption mass for γ rays,[3] these plates are neither truly γ-thin nor γ-thick. Thus, the rate of charge collection of each of these plates is given by[1]

$$\frac{dq}{dt} = \frac{2 \times 10^{-8}}{m_\gamma} \int \rho \bar{\dot{\gamma}}\, dV_{pl} \ ,$$

where $m_\gamma = 300\ kg/m^2$, ρ is the density of the plates in kilograms per cubic meter, $\bar{\dot{\gamma}}$ is the γ flux over all directions, and V_{pl} is the volume of the plates. Consider the radiation beam to be approximately in one direction, and let the flux be $\bar{\dot{\gamma}}_f$ at the front of the plate; then[1]

$$\frac{dq}{dt} = \frac{2 \times 10^{-8} A_{pl} \rho \dot{\gamma}_f}{m_\gamma} \int^{\ell} \exp\left(-\rho x/m_\gamma\right) dx \ ,$$

where A_{pl} is the cross-sectional area of each plate, ℓ is the length of each plate, and x is the distance. Integration yields

$$dq/dt = 2 \times 10^{-8} A_{pl} \dot{\gamma}_f \left[1 - \exp\left(-\rho \ell/m_\gamma\right)\right] \ . \tag{10}$$

The total charge deposited during the radiation pulse on each plate is then given by

$$q = 2 \times 10^{-8} A_{pl} D_{\gamma f} \left[1 - \exp\left(-\rho \ell/m_\gamma\right)\right] \ . \tag{11}$$

Since the front and the back plates of the box are γ-thin, the total charge collected by each is given by

$$q = 2 \times 10^{-8} M D_\gamma / m_\gamma \ , \tag{12}$$

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[1]*C. L. Longmire, Direct Interaction Effects in EMP, Mission Research Corp. LANC-N-12 (November 1973).*

[3]*R. D. Evans, The Atomic Nucleus, McGraw-Hill Book Co., Inc., New York (1955), 715.*

where M is the mass of each plate. If the total dose at the front of the box were 500 rads (Si), the total charge collected by the box would be 5.5×10^{-8} C. If the region between the boxes were a vacuum, the peak voltage generated would be 280 V. If the region between the boxes were filled with SF_6, about 150 V would be generated. If the region were filled with air, at most a few volts would be generated.

Current.--When the inner box is not filled with lead, the short-circuit current must be calculated by using equation (10) and the derivative of equation (12). At the 500-rad (Si) location, the short-circuit current should be 0.38 A.

3.1.2 Equivalent Circuit Model

An equivalent circuit model is being developed by HDL for calculating coupling in a radiation environment. Prior to the test, some preliminary predictions of the test geometry response were made, but subsequently it was discovered that the circuit employed was not completely adequate for that application. Consequently, those pretest predictions, which were erroneous, are not discussed here.

3.1.3 Compton Diode

The current collected by the Compton diode should be equal to

$$I = J_d A_{cl} , \tag{13}$$

where J_d is the Compton current density at the front of the diode, and A_{cl} is the exposed area of the collector. If the Compton diode were placed at a location where the total dose would be 500 rads (Si), and if the effective AURORA pulse width were 145 ns, then, from equation (2), the Compton current density at this location should be approximately 69 A/m^2. If the diameter of the collector were 2.5 in. (6.4 cm), then the current collected would be 0.22 A. If a 50-Ω cable were attached to the output of the Compton diode, the output voltage would be given by

$$V = IR_o ,$$

where R_o is equal to 50 Ω. Thus, the measured voltage would be 11 V.

3.1.4 Rogowski Coil

The current measured by a Rogowski coil is given by

$$I = J_c A_c , \tag{14}$$

where J_c is the Compton current density at the coil, and A_c is the effective area of the coil. If the diameter of the coil were 1.875 in. (4.76 cm), and if the coil were exposed to the same radiation environment as the Compton diode mentioned above, the collected current would be equal to 0.123 A. If the transfer impedance of the coil were equal to 2.4 Ω, then the output voltage would be 0.295 V.

3.1.5 Collimated Rogowski Coil

If the radiation incident on the Rogowski coil were collimated with a lead collimator, then the effective area of the Rogowski coil used in equation (14) would be reduced to the area of the collimator. If the collimator had a circular hole of 1-in. (2.54-cm) diameter, and if the Compton current density at the sensor were 69 A/m^2, then, from equation (14), the collected current would be 0.035 A, and the output voltage would be 0.084 V.

3.1.6 Collimated Dosimeter Experiments

Although it may sometimes be assumed so, the AURORA flash x-ray machine is not a point source of radiation. A more reasonable assumption is that it is a disk source of some effective area. To determine this area, an experiment was designed using TLD's placed in holes drilled through various thicknesses of lead bricks. By measuring the dose and dose rates at the same distance from the source employing 0, 2, and 4 in. (0, 5.1, and 10.2 cm) of collimation, then the effective area of the source can be calculated directly by geometrical considerations. This calculation is based on the assumptions that no γ-radiation scattering takes place in the collimating tube and that no radiation traverses the lead directly. In reality, neither of these assumptions is valid, but possibly somewhat reasonable for the purposes at hand. To determine the effective area of the AURORA source, it was assumed that the radiation emanates uniformly from a disk of some radius at the test chamber wall. For an uncollimated dosimeter, the measured dose is the sum of the contributions from the entire disk. But, if the dosimeter is placed behind some collimation, the dose is contributed only from a portion of the disk, depending on the distance and length of collimation involved. The area of the source can be calculated from the expression

$$A_s = \left(r_{contributing}\right)^2 \pi \, D_u/D_c \; ,$$

where

A_s = effective area of source,
$r_{contributing}$ = radius of disk contributing to dosimeter,
D_u = uncollimated dose measurement,
D_c = collimated dose measurement.

3.2 Special Instrumentation

A cathode follower circuit was employed as an impedance matching network to drive the low impedance (50 Ω) cable while making a high impedance (10 MΩ) measurement so that signals sufficiently above noise levels remained. The cathode follower was selected because of the high input impedance (1 MΩ) and low output impedance (50Ω) coupled with a gain of 0.7. In addition, the cathode follower (of tube rather than solid state design) was expected to operate in a radiation environment. The circuit for the cathode followers employed for this test is given in figure 3. Initial check-out of the breadboard circuit indicated that the dynamic range of the cathode follower could be expected to be from about +10 to -3 V. The final assembled versions were checked out and indicated a dynamic range from +10 to -3 V and a bandwidth of 29 MHz

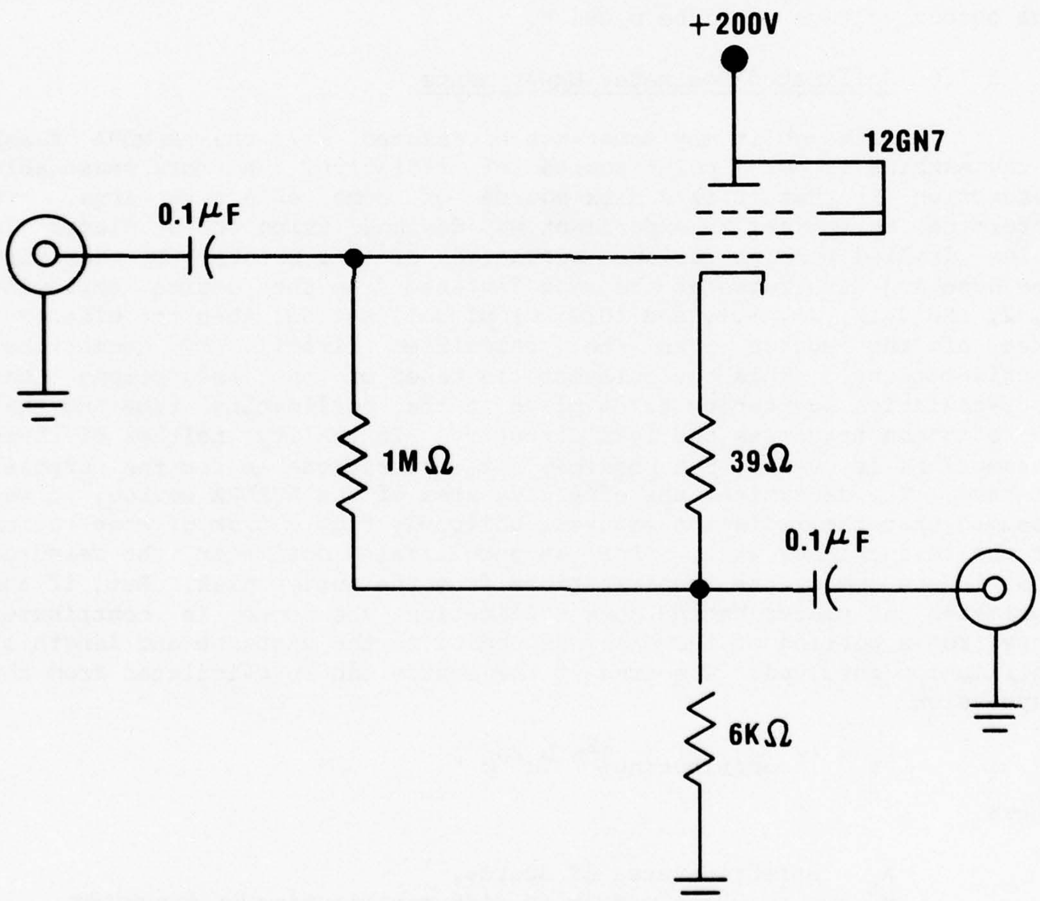

Figure 3. Cathode follower circuit.

operating in a nonradiation environment. In the final placement during the test, the cathode followers were shielded with lead so that they were exposed to a total dose of 0.5 rads (Si).

3.3 Posttest Checkout

After the test, all of the instrumentation and probes were checked by using standard signal sources to insure that calibration was maintained during the test.

4. TEST PROCEDURES

The test chamber was placed at a location 2.9 m from the front test cell wall on the axis of the radiation. In this position, the total dose predicted at the front of the test chamber was 700 rads (Si) (with the machine charged to 90 kV). The series of shots was conducted with the primary measurement and the absorber specified in table I.

TABLE I. SHOT SCHEDULE.

Shot Series	Configuration	Measurement
1	γ-thin	Current
2	γ-thin	Current
3	γ-thin	Voltage
4	γ-thick	Voltage
5	γ-thick	Current
6	γ-thick	Current
7	γ-thick	Voltage
8	γ-thin	Voltage
9	γ-thick	Voltage
10	γ-thick	Voltage
11	γ-thick	Voltage
12	γ-thin	Voltage
13	γ-thin	Voltage

Twenty-eight oscilloscope channels recorded the data; 12 channels were dedicated to the primary measurement (either current or voltage on the absorber), and 16 were used to monitor cable noise or to record data on the external sensors. In addition, during the first two shots, Rogowski coils (measuring Compton current) and Moebius loops (measuring magnetic field) were placed inside the upper chamber, and the data were recorded. During the remaining shots, though, the test chamber was free of sensors, with the exception of the thin wire connecting the suspended absorber and the data-taking point at the wall separating the two chambers.

Prior to each shot, initial estimates of the peak signals were reviewed, and a series of data channels was dedicated to each measurement with amplitude setting bracketing the predicted signal level. In this way, there was reasonable assurance that at least one oscilloscope trace would provide meaningful data.

After each shot, the shot number was recorded on the oscilloscope pictures, and the pictures were placed in an album, along with sensor

information and amplitude and time settings. In addition, notes on the experimental setup were recorded.

5. DATA REDUCTION

Data obtained during AURORA tests consist of pictures of oscilloscope traces. Unfortunately, it is not a simple task to relate the pulses appearing on these pictures to the currents, fields, etc., which are being generated within or upon an experimental configuration placed within the AURORA test cell. Sensors such as current probes and Moebius loops have response functions and certain electronic limitations which must be taken into consideration when analyzing their output. Cables tend to reduce the signals passing through them, and this reduction is frequency dependent. Consequently, a frequency-dependent transfer function representing the characteristics of the sensor-cable-balun measuring system used at AURORA is measured with a network analyzer.

The following procedure is used to analyze the data taken during AURORA experiments: The oscilloscope pictures are digitized, and the digitized information is stored on a computer disk file. This information is read into a program which plots the data. The plot is compared with the oscilloscope picture, and any needed corrections are made to the digitized data. The digitized information is then read off the disk file by a computer code developed at HDL, which numerically transforms the digitized data into the frequency domain, multiplies the frequency domain representation by the appropriate transfer function, transforms this information back into the time domain, multiplies the result by the appropriate sensor response and conversion factors, and plots the resultant information. The plotted information represents the time histories of the actual fields, currents, etc., occurring at the sensor locations during the AURORA tests, not merely measured voltages. These plots are then compared with theoretical predictions of test results.

6. TEST RESULTS

6.1 Voltage Measurements, Compton Diode and Rogowski Coil

The voltage measurements with the cathode followers and the Compton current measurements with the Compton diode and with the collimated Rogowski coil were all unsuccessful. Despite the fact that the cathode followers were shielded with lead, the small amount of radiation which reached them produced transient radiation effects on electronics (TREE), which rendered them useless. The direct coupling to the coaxial cable used with the Compton diode was of the order of the

signals being measured, so that the measurements had no value. Also, the collimator used with the Rogowski coil reduced the signal so that it was lost in the cable noise.

The output of the Rogowski coils was processed by the computer code mentioned previously; the resultant plots of the Compton current time histories are shown in figures 4 to 8. Table II lists the peak Compton currents calculated from equation (2) and those obtained from the plots shown in figures 4 to 8. Sensor RC2 was used within the larger box, and sensor RC4 was used directly in the AURORA test cell.

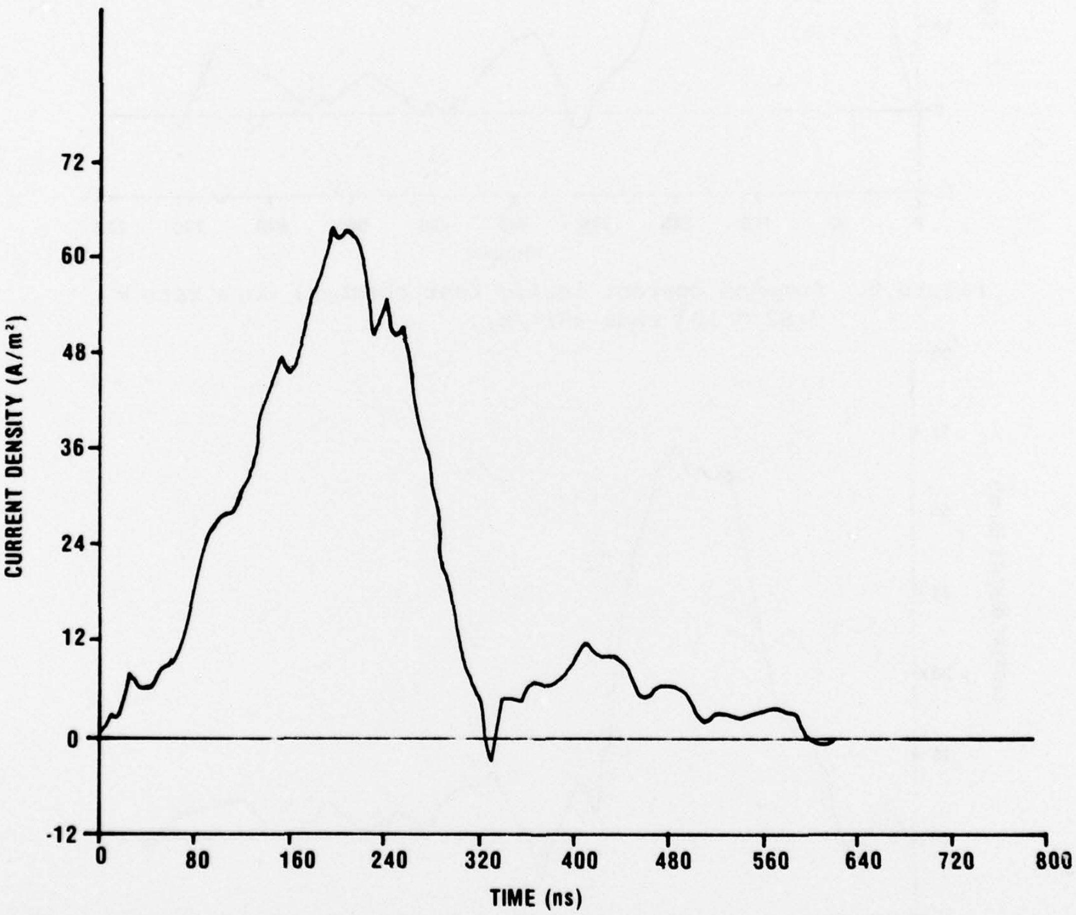

Figure 4. Compton current inside test chamber; dose rate = 4.01×10^9 rads (Si)/s.

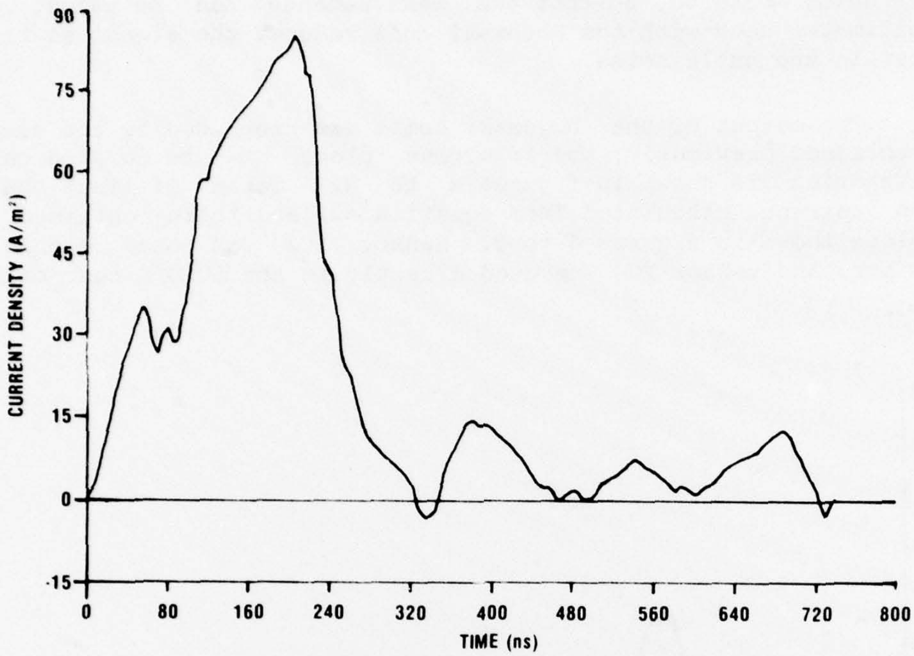

Figure 5. Compton current inside test chamber; dose rate = 3.82×10^9 rads (Si)/s.

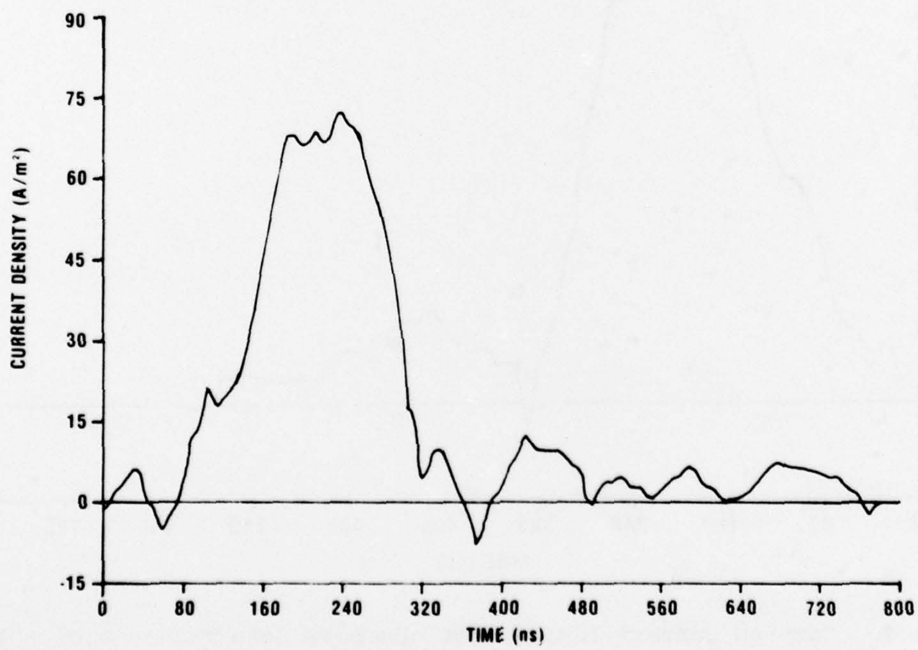

Figure 6. Compton current inside test chamber; dose rate = 4.06×10^9 rads (Si)/s.

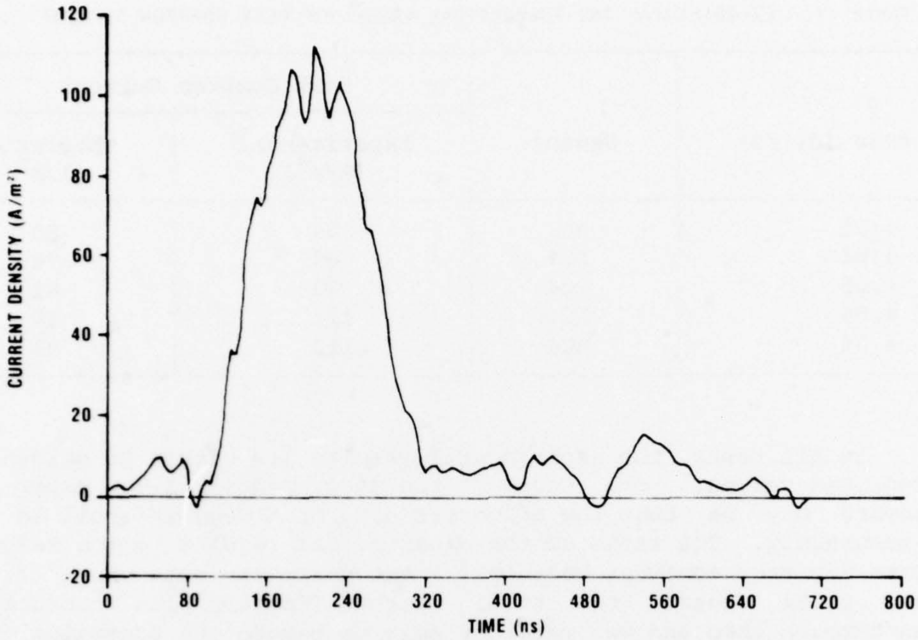

Figure 7. Compton current inside test chamber; dose rate = 4.94×10^9 rads (Si)/s.

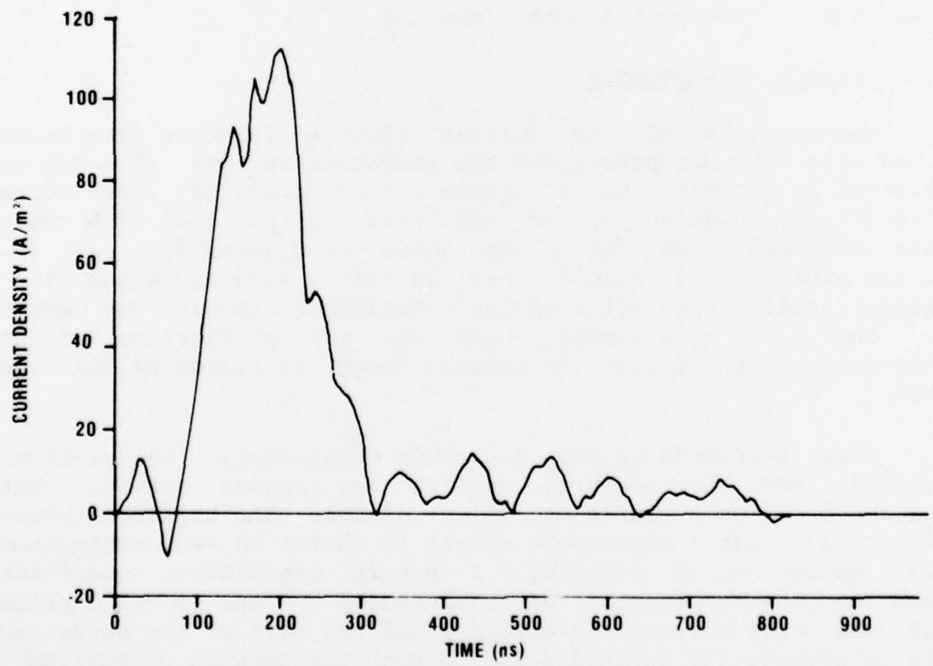

Figure 8. Compton current inside test chamber; dose rate = 4.64×10^9 rads (Si)/s.

TABLE II. EXPERIMENTAL AND THEORETICAL VALUES OF PEAK COMPTON CURRENT.

$\dot{\gamma}$ ($\times 10^9$ rads (Si)/s)	Sensor	Peak Compton Current	
		Experimental (A/m^2)	Theoretical (A/m^2)
4.01	RC2	64	80
3.82	RC4	85	76
4.06	RC4	73	81
4.94	RC4	112	99
4.64	RC4	112	93

In all tests, the experimental results are within 20 percent of the predicted values. One cause of the discrepancy between experiment and theory may be that the effective area of a Rogowski coil is not known accurately. The ratio of the experimental results to the measured dose rate may vary somewhat because (1) the dosimetry data vary; (2) the Rogowski coils measure the total current (Compton plus conduction) passing through them and we were not able to remove the contribution of the conduction currents to the measured values; and (3) the Rogowski coils do not measure only totally axial currents, but respond to all currents passing through the center opening.

6.2 Current Measurements

Measurements of the current flowing from the free-floating inner box also were processed, and the resultant current time histories are plotted in figures 9 to 11. Table III compares the peak currents calculated from equation (9) or equations (10) and (12) with the peak currents obtained from the plots shown in figures 9 to 11. In all tests, the experimental results are in fairly good agreement with the theoretical predictions, although the experimental results are somewhat lower. Thus, the simple model used for the predictions of these currents seems quite adequate in making rough estimates of the coupled currents.

This agreement between the crude quasi-static calculation of the current and the measured current may appear trivial, but a calculation based on a simple equivalent circuit that neglects inductive couplings and yields a reasonable answer is useful in the estimation of tactical source-region coupling. A purely capacitive, quasi-static approach to the estimation of the measured current is valid probably because the wire between the absorber and the wall of the outer cubic chamber is essentially perpendicular to both the Compton current and the magnetic field resulting from the Compton current.

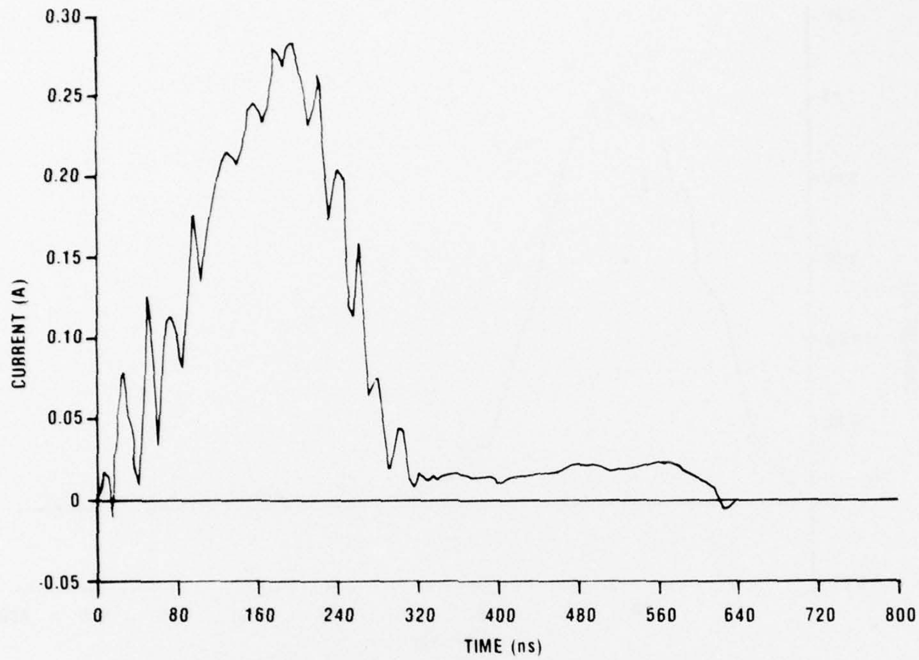

Figure 9. Current coupled to γ-thin inner box; dose = 497 rads (Si).

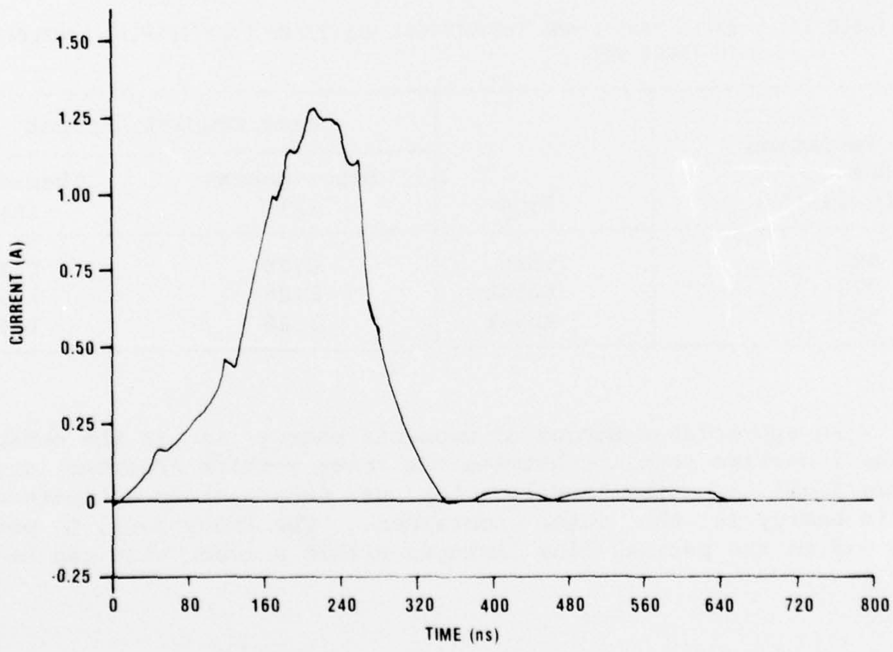

Figure 10. Current coupled to γ-thick inner box; dose = 520 rads (Si).

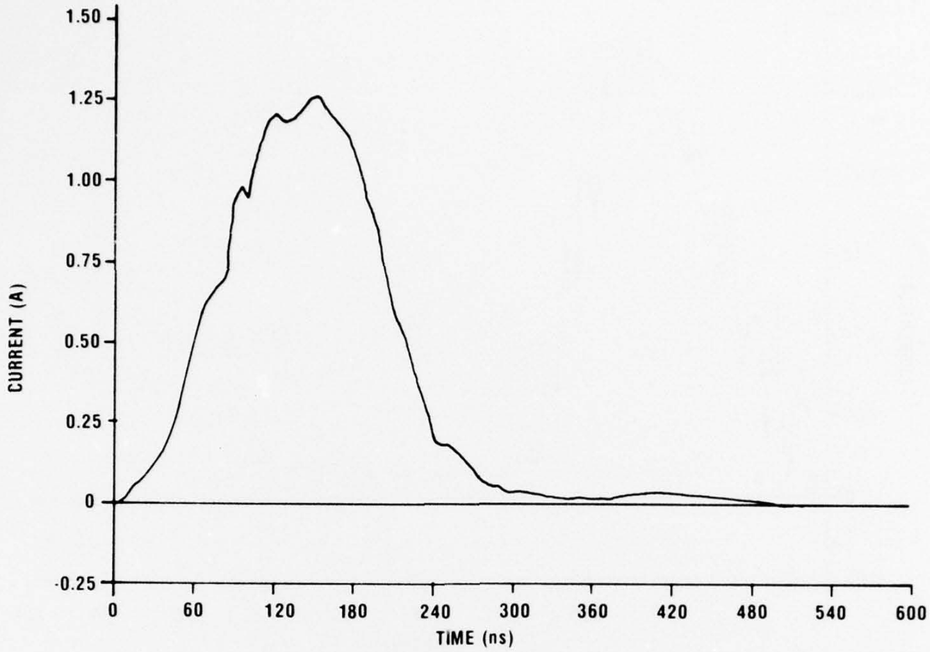

Figure 11. Current coupled to γ-thick inner box; dose = 567 rads (Si).

TABLE III. EXPERIMENTAL AND THEORETICAL VALUES OF PEAK CURRENT COUPLED TO INNER BOX.

Total radiation dose (rads (Si))	Type	Peak Coupled Current	
		Experimental (A)	Theoretical (A)
497	thin	0.28	0.32
520	thick	1.28	1.63
567	thick	1.26	1.82

An appreciable amount of magnetic energy is in the outer box, but the inductive coupling between the inner γ-thick absorber and the magnetic field is very small. Let us make a crude estimate of the magnetic energy in the outer container. The inductance, L, per unit length due to the partial flux linkages within a round wire can be shown to be

$$L = \mu_o/8\pi \ ,$$

where μ_o is the permeability of free space. If we approximate the square outer box with a round box of equal area, the inductance of the Compton current passing through the box is given by

$$L = \left(\mu_o/8\pi \ \ell_b\right),$$

where ℓ_b is the length of the box parallel to the Compton current. Let us now compare the magnitude of the capacitive energy between the concentric boxes and the magnetic energy in the outer box. That is, let us compare $CV^2/2$ with $LI^2/2$. The Compton current (I) through the box is $I = JA_o$, where A_o is the area of the outer box.

We find that

$$CV^2/2 = 2.05 \times 10^{-7} \text{ MKS units },$$

$$LI^2/2 = 2.50 \times 10^{-6} \text{ MKS units }.$$

In other words, a significant amount of energy is stored in the magnetic field, but it is not coupled into the wire between the concentric boxes.

Even if the ability to separate inductive and capacitive interactions were a tool limited only to ideal, experimentally controllable geometries, this tool would greatly simplify the design and understanding of experiments. When considering lumped element equivalent circuits of a particular experimental configuration, it is much simpler to deal only with resistors and capacitors than with resistors, capacitors, inductors, and transformers. If the lumped parameters in our equivalent circuit were time varying and nonlinear, the above result would be of even greater significance.

6.3 Collimation Experiment

From the equations in section 3, the effective area of the AURORA source was calculated to be 2209 in.^{2} (1.425 m^2) resulting from the 2-in. (2.54-cm) collimation data and 1346 in.^{2} (0.868 m^2) resulting from the 4-in. (10.2-cm) collimation data. This calculation implies that the AURORA source can be approximated by a disk whose radius is about 20 to 26 in. (50.8 to 66 cm).

7. CONCLUSIONS

The cathode follower, which was to be used to make a high impedance voltage measurement in the AURORA radiation environment, was not

successful because of TREE on the voltage probe and the cathode follower. When the capacitance of the probe was not adequately compensated because of TREE, the signal was severely distorted. In addition, the dose rate measured at the cathode follower was sufficient to indicate that the instrument could be severely upset.

Therefore, it was concluded that a compensated high voltage probe should be constructed to function in the AURORA radiation environment. Further, it was decided that the March test plan should be modified to specify that a greater amount of lead shielding be placed around the cathode followers so that the dose rate would be sufficiently reduced below the expected upset level.

The Compton diode data indicated that the Compton current was not successfully being measured by the instrument. Because of the collimation problems, it was decided that this method of measuring Compton current should not be pursued in the March test.

Finally, for some configurations, a simple coupling model which considers only direct interaction effects might be sufficient to predict responses. One must be extremely careful, however, in implementing such a model.

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